

# INITIAL TEST RESULTS FOR A NEW PPS GPS TIMING RECEIVER

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## *Abstract*

*A new Global Positioning System (GPS) timing receiver has been built for the U.S. Naval Observatory (USNO). The new receiver is a 12-channel Precise Positioning Service (PPS) unit capable of tracking GPS Y-Code signals and internally removing the effects of Selective Availability. It is based on the receiver being used in the GPS Monitor Stations by the GPS Control Segment.*

*Testing is being done at the Naval Research Laboratory (NRL) using the GPS signal simulator. The NRL simulator is capable of producing 10 simultaneous signals with Selective Availability and Y-Code. Initial test results show that prior problems with timing calibration due to uncertainties in the initial conditions in the receiver have been shown to be stable to less than one nanosecond with small bias. Additional data will be presented showing the measured effects of temperature on the receiver.*

## INTRODUCTION

The Master Clock of the U.S. Naval Observatory (USNO) is the official time reference of the United States as designated by the Joint Chiefs of Staff (JCS) Master Navigation and Timing Plan and the joint Department of Defense/Department of Transportation Radionavigation Plan. The Department of Defense (DoD), most civilian government agencies, and private industry rely on the USNO Master Clock for their source of precise time. As part of the USNO timekeeping mission, USNO serves as the precise time reference for the Global Positioning System (GPS).

USNO measures the GPS system time offset relative to the USNO Master Clock located in Washington DC using specialized monitor station GPS timing receivers. These measurements are analyzed and sent daily to the GPS Control Segment, which then corrects the GPS time scale to match the DOD Master Clock at USNO. Over the last three years the GPS time scale has been maintained to within 10 nanoseconds of USNO time.

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Each GPS satellite continuously broadcasts the necessary parameters to correct for leap seconds and to extract an even better realization of UTC (USNO) as part of each GPS satellite's data message. GPS receivers, both civilian and military, use this information to reproduce USNO time with accuracies of better than one microsecond with the potential of 10-nanosecond accuracies when averaged over a few hours, all for the cost of a few thousand dollars. Thus, the Global Positioning System (GPS) is one of the most precise and cost-effective methods of disseminating precise time.

## **GPS TIME MONITORING EQUIPMENT**

Currently USNO uses the STel 5401C GPS (P/Y) Code timing receivers to monitor the GPS time offset. These receivers are based on a single satellite tracking, dual-frequency, P/Y Code receiver that was developed in the mid 1980's. Because this receiver has only a single tracking channel, a tracking schedule must be used to ensure complete coverage of all GPS satellites. The internal time interval counters in these receivers have a resolution of only 9 nanoseconds. Therefore, to improve the precision of the measurements, an external counter is used. Also, the receivers are not GPS 1024 week number rollover-compliant. When the GPS week number rollover occurred, the receivers began displaying January 6, 1980 and the time tag on the data was incorrect. The epoch of the data must now be corrected before the data can be processed.

Despite these shortcomings the STel 5401C receivers have proven to have excellent long-term stability. Figure 1 shows a long-term comparison of the stability between two STel 5401C receivers with the USNO Two-Way Satellite Time Transfer link between USNO Washington DC and the USNO Alternate Master Clock in Colorado Springs.

Due to the age and technical limitations of these STel 5401C GPS receivers, it was apparent that a next generation GPS time monitor receiver had to be developed. This next generation time monitor receiver would be used to track the P/Y code of all GPS satellites in view on both L1 and L2 frequencies and under all conditions of Selective Availability (S/A). A modern all digital design would allow sub-nanosecond time interval measurements and should provide improved long- and short-term stability. It was also required that the receiver would be stable to within one nanosecond over a temperature range of +/- 5 degrees centigrade. The receiver would also output all raw broadcast parameters, as well as all code and carrier-phase measurements.

## **RECEIVER DEVELOPMENT**

Two GPS receiver manufacturers were contracted to develop a prototype receiver. They were Allen Osborne Associates (AOA) and NAVSYS Corporation (NAVSYS). Each company was to independently develop a receiver based on a set of specifications provided by the USNO. The AOA receiver would be an enhanced version of their new GPS Monitor Station Receiver Element (MSRE). The NAVSYS GPS receiver would be an enhanced version of their High Gain Advanced GPS Receiver (HAGR), which was derived from their WAAS reference station receiver. A comprehensive test program was developed to support this program, with testing to be conducted at AOA, NAVSYS, USNO, and the NRL GPS calibration and simulation test facility.

### **AOA TTR-12 Receiver**

The AOA TTR-12 timing receiver is a derivative of the Jet Propulsion Laboratory (JPL) Rogue family of Geodetic GPS receivers. AOA chose to build this receiver based on their new BenchMark/TurboRogue geodetic GPS receiver with ACT technology, as well as the recently developed GPS monitor station receiver.

This receiver tracks up to 12 satellites simultaneously and provides all six code and carrier observables, whether the P-Code encryption (A-S) is on or off. It outputs carrier phase and pseudo-range measurements derived from L1-C/A, L1-P/Y, and L2-P/Y code with full carrier wavelength. The ACT code tracking technology improves upon the P-codeless technique of older generations of Rogue receivers, resulting in an increase of the SNR on L2 and, thus, reduced measurement noise.

During normal operation the TTR-12 receiver will track the true P/Y code GPS signal. When the receiver is operated unkeyed, the TTR-12 will revert to this ACT code-tracking mode with minimal loss of precision. A 100 picosecond time-interval counter was integrated into the AOA design to allow the internal measurements to be related to an external clock.

### **NAVSYS Timing Receiver**

The NAVSYS receiver is based on their High Gain Advanced GPS Receiver (HAGR). The HAGR was developed to allow phase coherent measurements to be made from multiple antenna elements to enable digital beam forming. In this NAVSYS design a sixteen (16) element L1 and L2 phased array antenna system is employed in a way that allows the signals to be combined to provide gain to each of the GPS satellites being tracked. The resulting increase in signal-to-noise ratio will greatly decrease the code measurement noise and the directivity provided will reduce the effects of multi-path. The resulting improved code measurements can be used in near real time to resolve the carrier-phase ambiguity. The HAGR design provides a highly phase-stable observation of the GPS carrier, relative to a local reference oscillator. This enables precise time observations for use in carrier-phase time transfer. The prototype receiver under development will track up to eight GPS satellites simultaneously with either a single element antenna or the optional 16-element array antenna.

### **Testing to Date**

Early developmental testing of these receivers at each of the companies and at NRL and USNO uncovered numerous problems. The most serious problems centered on how the external reference clock is related to the receivers internal pseudo-range and carrier-phase measurements. Once these problems were overcome, the rest of the developmental phase centered on verification that the receiver-calculated corrections to the pseudo-range measurements were correct.

Figure 2 shows test data of the AOA TTR-12 receiver measurement noise and inter-channel biases. Because of the digital nature of the TTR-12, the inter-channel biases are negligible ( $< 100$  picoseconds). This simulator test demonstrates that the error contribution of the receiver to the overall measurement of the GPS system time errors should be less than 500 picoseconds. This is an improvement of greater than tenfold over

the STel 5401C receiver. Multi-path will now dominate the short-term measurement noise of the new receiver.

Figure 3 shows power cycle retrace testing results of the NAVSYS GPS receiver done to determine the receiver's ability to hold its calibration after loss of power. Two NAVSYS GPS receivers were operated from a common antenna and clock (zero-baseline test) and the results were differenced to cancel out errors such as multi-path, local clock, and GPS system errors. Each data point represents a 60-second average of all common-view C/A code data collected on each of the receiver's eight channels. Then the power on one of the two NAVSYS receivers was re-cycled and a new 60 seconds of data were collected. The data showed that the receiver did indeed hold its calibration across power cycles to within the measurement noise (500 picoseconds).

### **NRL/USNO Receiver Test Plan**

After completion of the GPS time monitor station receiver development program, a 6-month effort of live testing at USNO and simulator testing at NRL is planned before the new receivers can be placed in operation at USNO. This testing should begin in early spring 2000 and be completed by the end of the summer 2000.

The Naval Research Laboratory is the designated DOD test agency for GPS timing receiver testing. USNO and NRL have jointly developed a detailed test plan to fully characterize the performance of these new GPS time monitor receivers. This includes a detailed study of the receivers' absolute calibration and the stability of this calibration over a variety of environmental conditions.

The NRL GPS calibration and simulation test facility consists of several highly accurate 10-channel dual frequency P/Y code GPS simulators. Each of the NRL simulators is capable of nanosecond-level calibration and simulation of both fixed and moving GPS scenarios. The NRL simulators can also be used to calibrate L1/L2 and inter-channel biases, test the receivers under all conditions of SA and AS, and provide a clean reliable reference for temperature characterization. Specially designed anechoic test chambers are available for calibrating the delays through the GPS antenna and antenna electronics. NRL has three Sigma Tau and two SAO Hydrogen Maser clocks available for use as precise frequency references. These reference clocks are tied to the DOD Master Clock at the USNO via a local TV-5 carrier-phase comparison system with an uncertainty of better than 200 picoseconds.

### **NRL/USNO Receiver Test Outline**

Verify raw pseudo-range measurement accuracy and stability.

Verify receiver corrections:

1. Ionosphere Measurements
2. Ionosphere Model Calculations
3. Relativity Correction Calculations
4. Troposphere Model Calculations
5. SV Clock Correction Calculations

## 6. UTC Clock Calculations

## 7. Selective Availability Calculations.

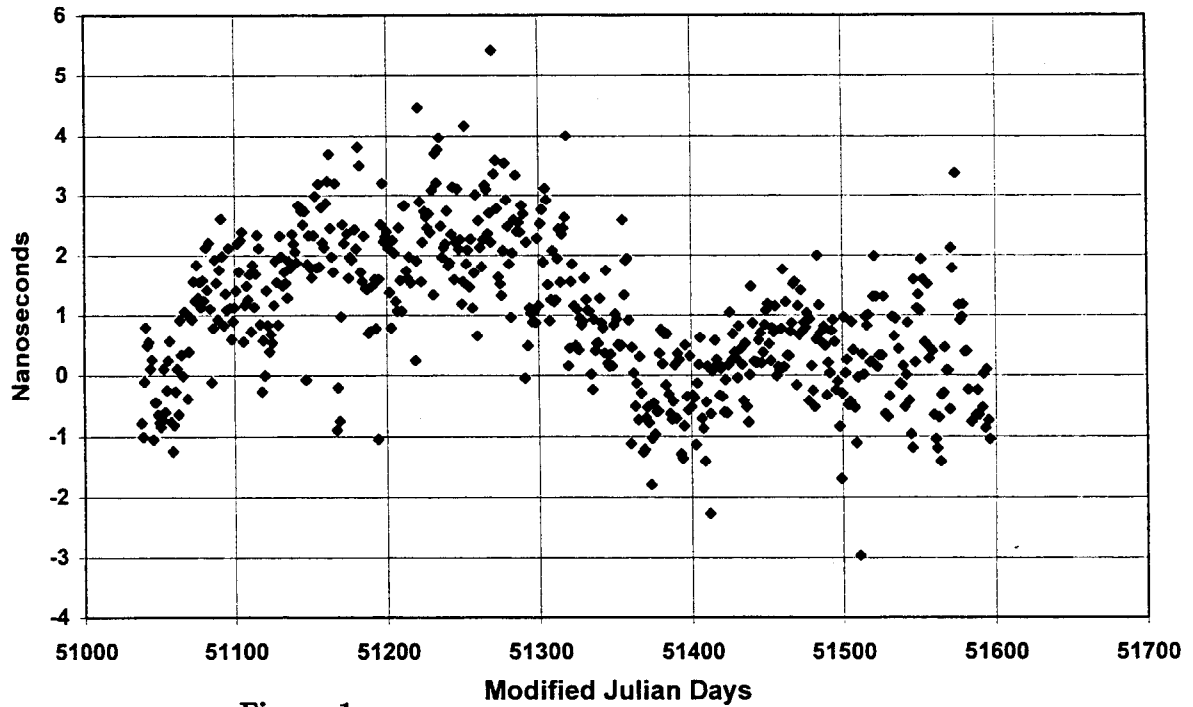
Characterization using live and GPS simulators:

1. Time accuracy temperature/humidity sensitivity tests
2. Power cycle time accuracy retrace tests
3. Long-term calibration accuracy aging tests.

## CONCLUSIONS

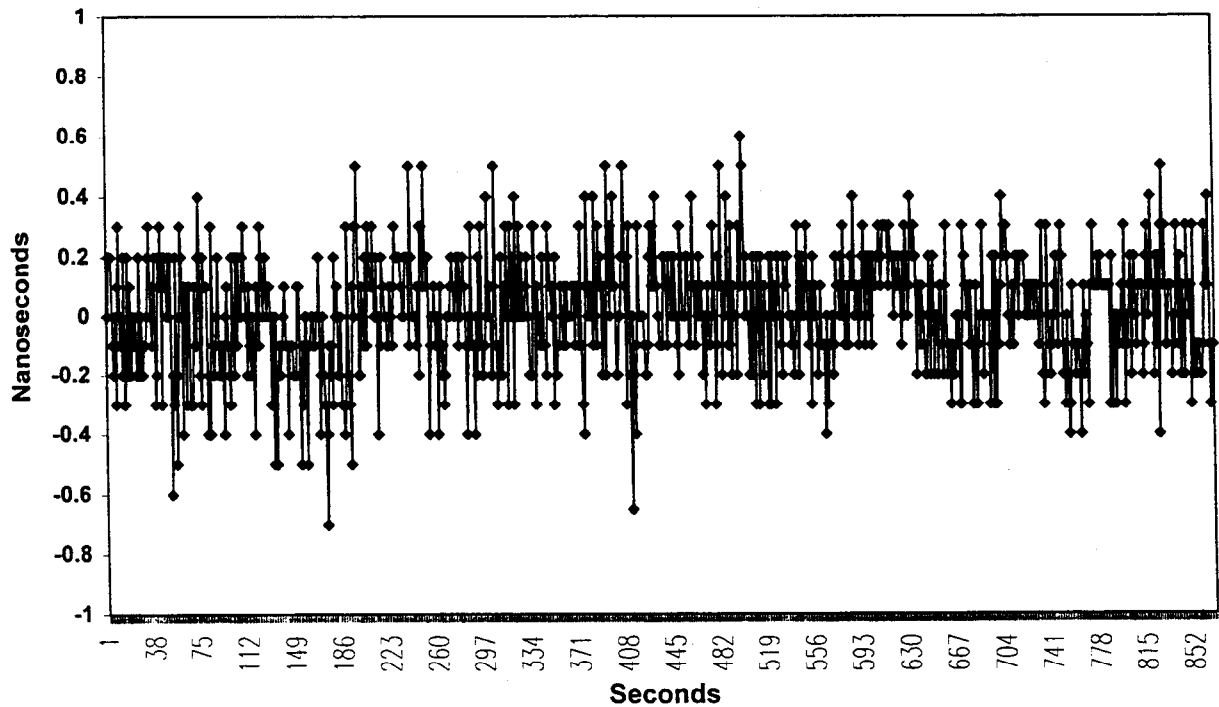
USNO has contracted with two vendors to develop a next generation GPS time monitor receiver. Preliminary testing has shown improvements of the short-term measurement noise of these new GPS receivers. This, coupled with the all in view receiver technology, improved thermal stability, and the almost all digital design should greatly reduce the timing error contribution of the USNO time monitor receiver to the GPS time error budget.

**Daily Double Difference Time Transfer (USNO(DC) - USNO(AMC))  
via Two Way and PPS Common View (2000 Mile Baseline)**



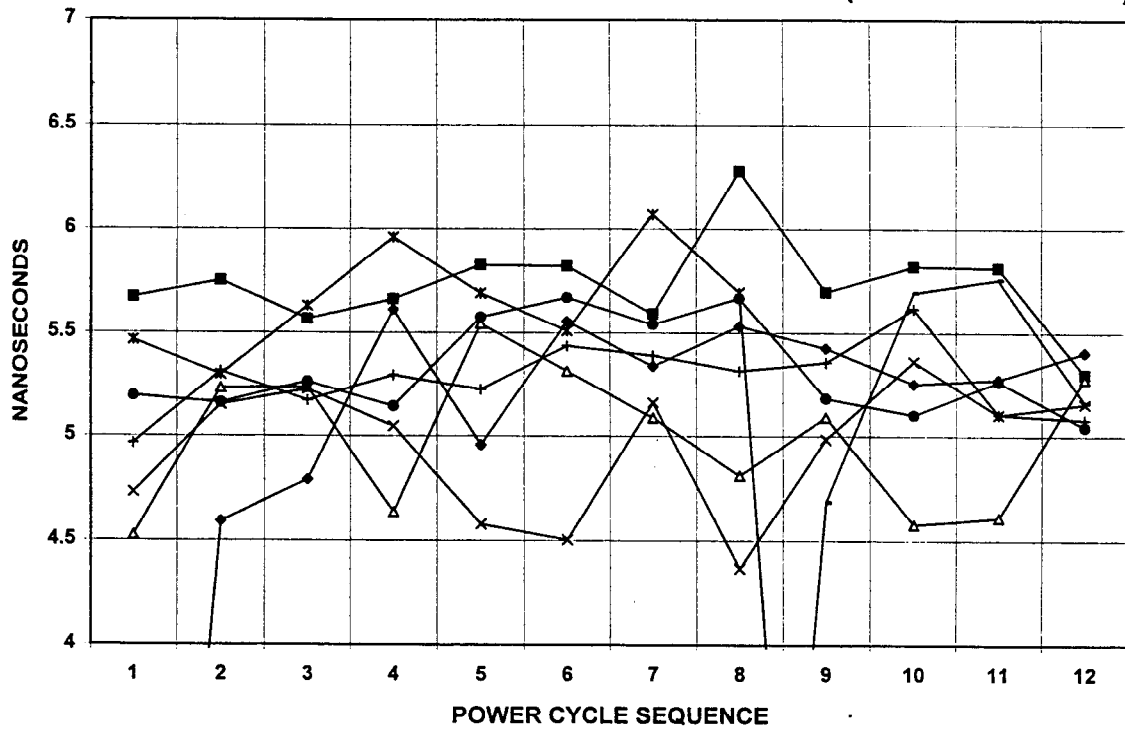
**Figure 1**

**AOA TTR-12 PPS Time Monitor Station Receiver Measurement Noise  
Tracking GPS Simulator**



**Figure 2**

**NAVSYS ZERO BASELINE TIME TRANSFER GPS RECEIVER  
POWER CYCLE RE-TRACE TEST RESULTS (ALL CHANNELS)**



**Figure 3**